Contents

- Neutron Generation

- Hadron Therapy

- Security

DT Neutron Generator

David Chichester: Idaho National Laboratory

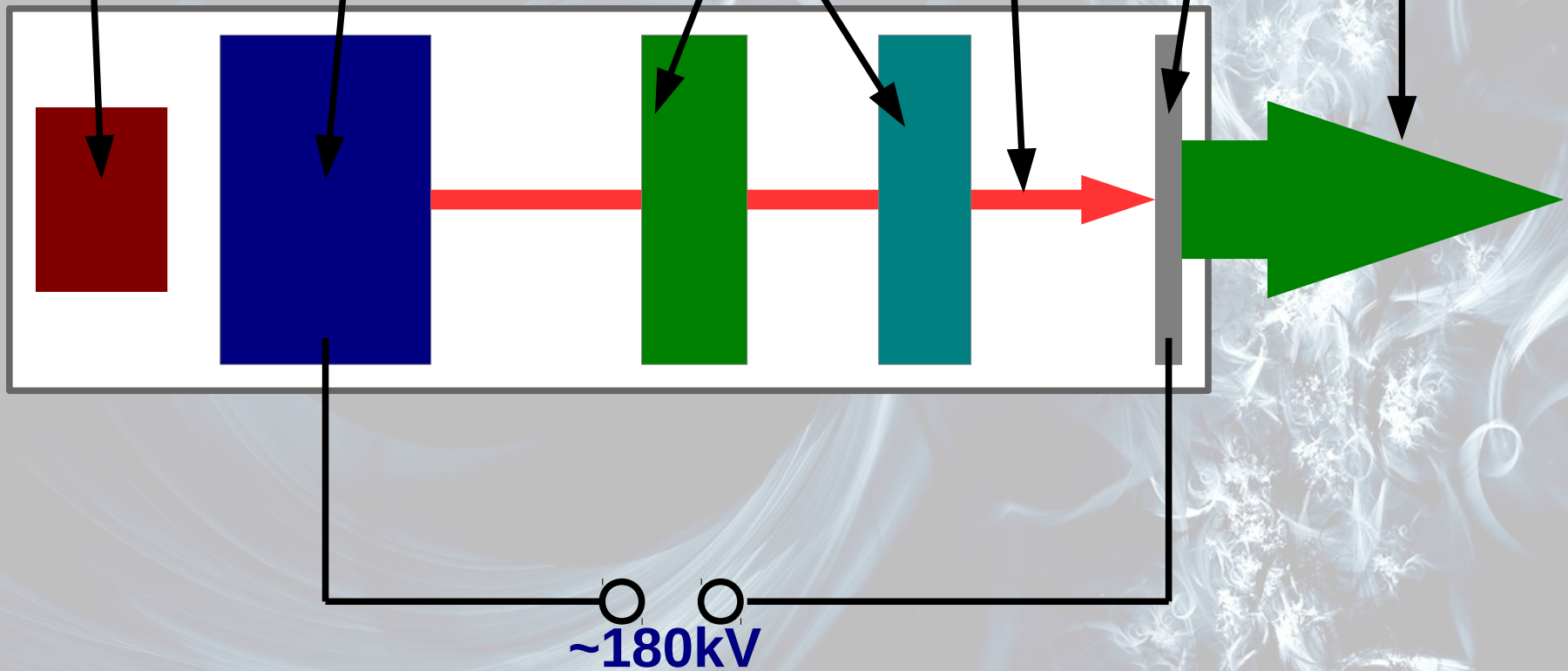- Tritium use/production undesirable

- Alternative combinations possible

- Broad range of applications:
  - Security – neutron scanning
  - Medicine – BNCT
  - Medicine – Radioisotopes
  - Industry – NDT
  - …
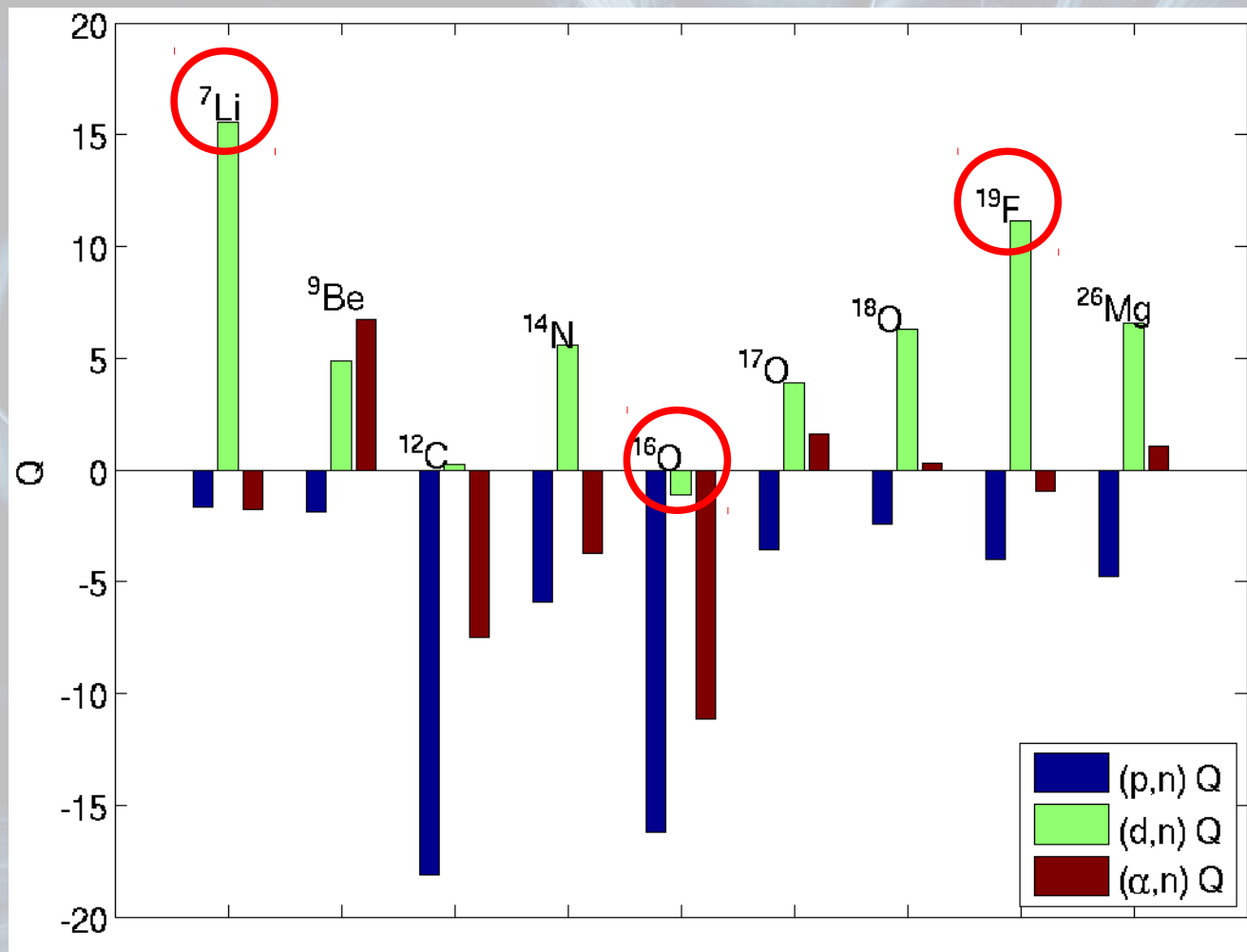
O(d,n)

Low Q
(^{17}F $T_{1/2}$ = 64s)

(almost) No E_n data
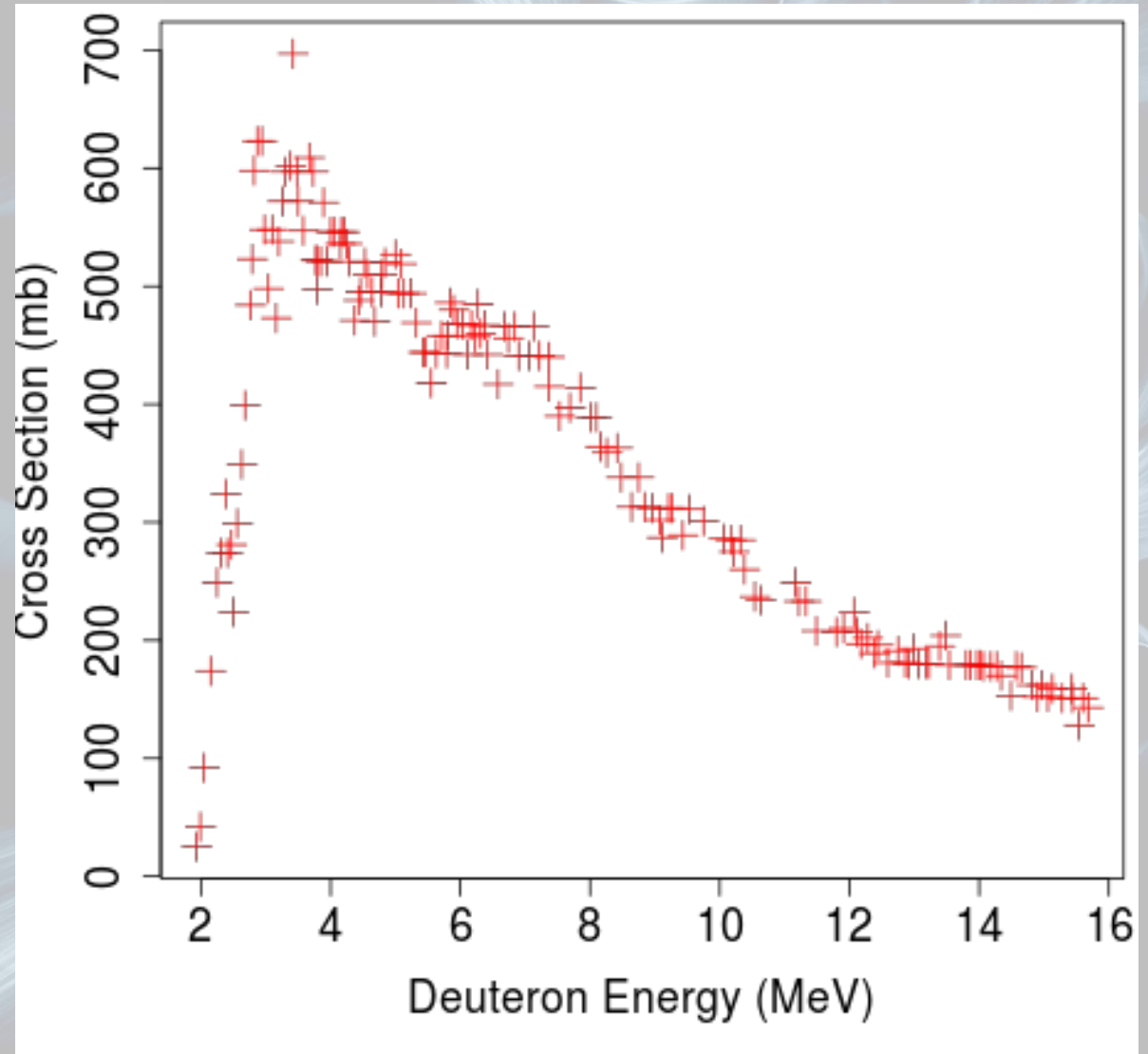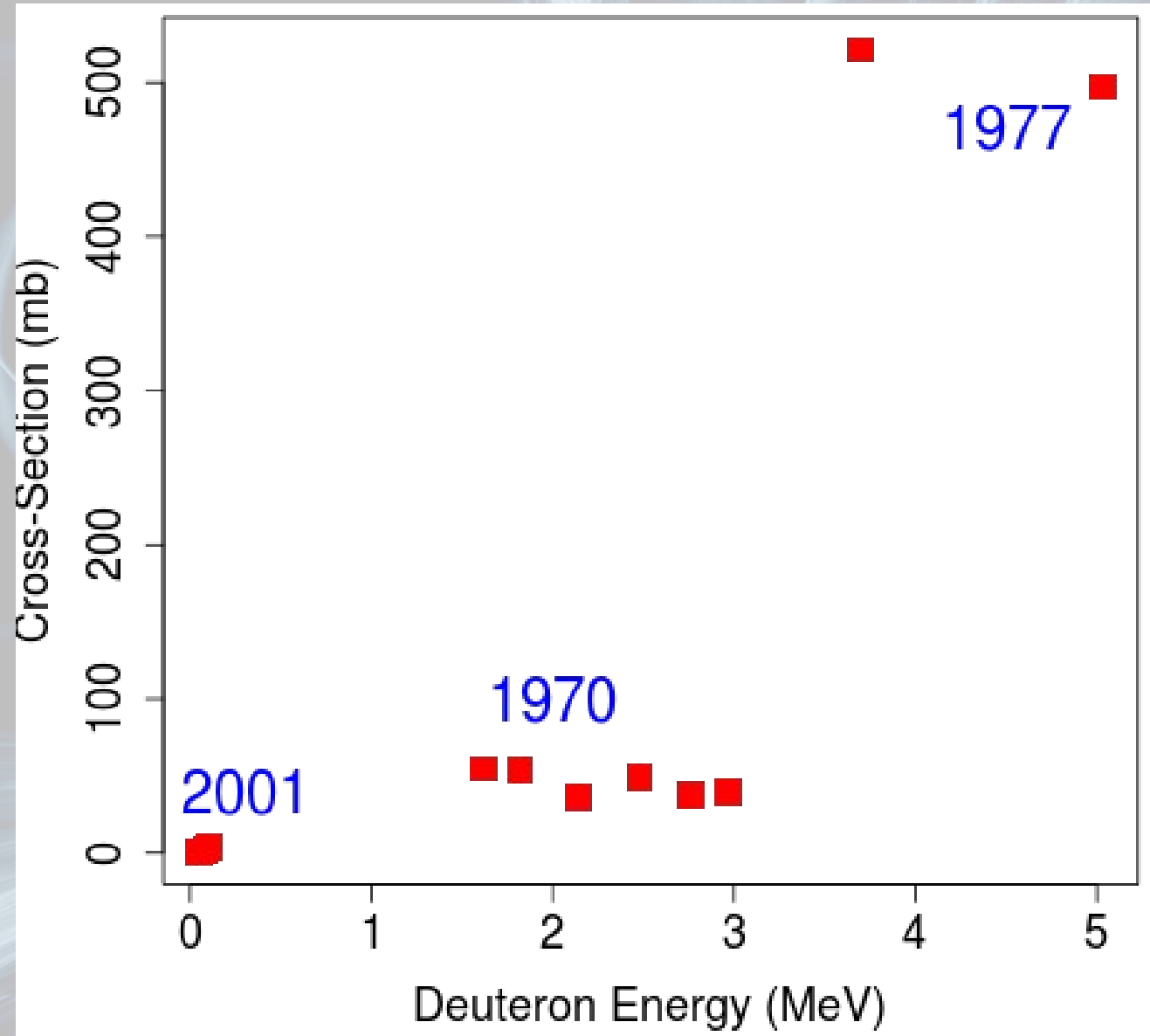
$^{19}F(d,n)$

High Q
Clean (20Ne stable)

Limited dE/dθ data

Energy Spectrum

(Approximate) energy
can be calculated
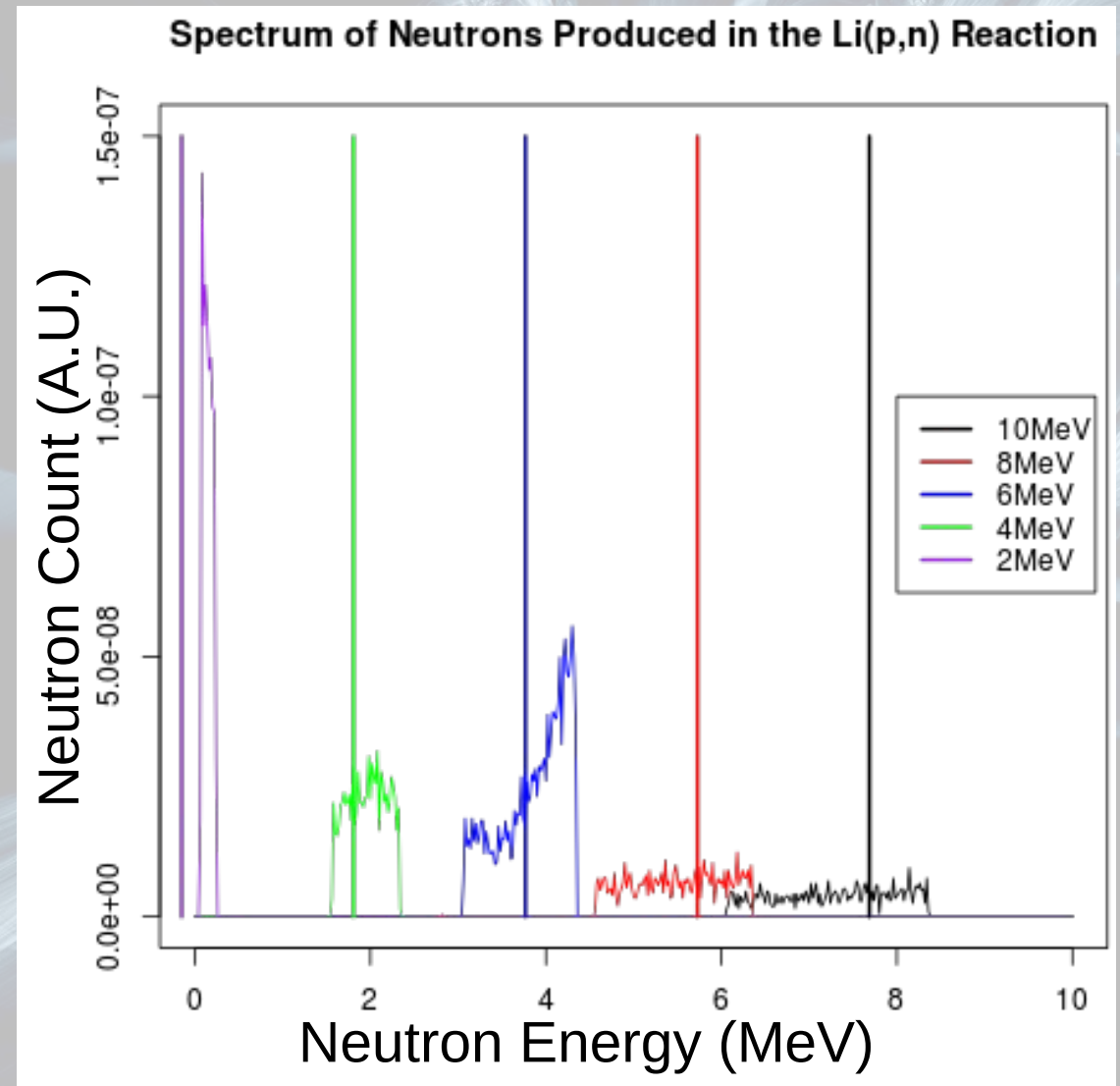
Energy Spectrum

- Less data available than for cross-sections

- Number of peaks and width is variable

- Some applications very spectrum dependant
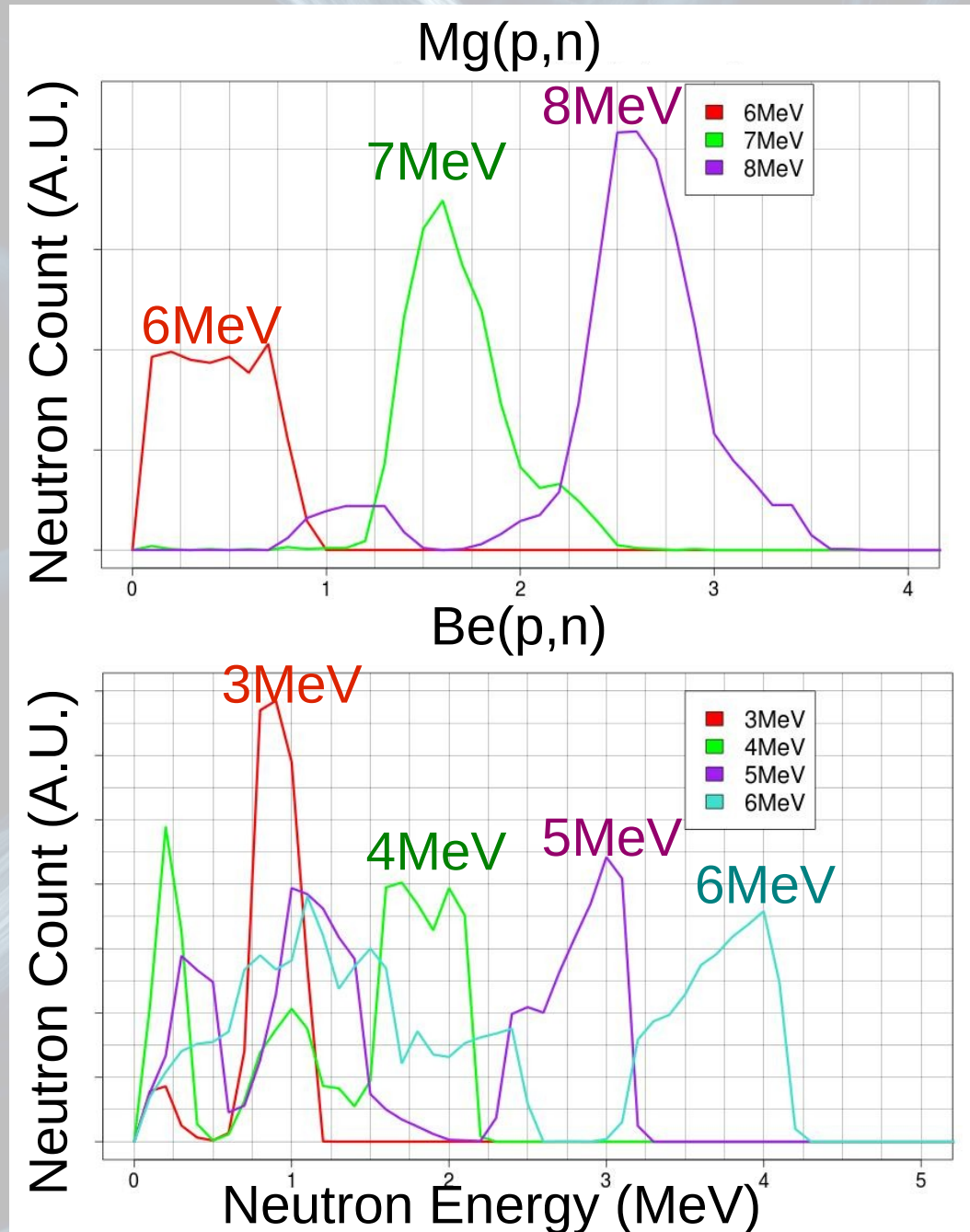
Lack of data problematic for
source selection

30 MeV Tandem suited to
study of low energy
compound nucleus reactions
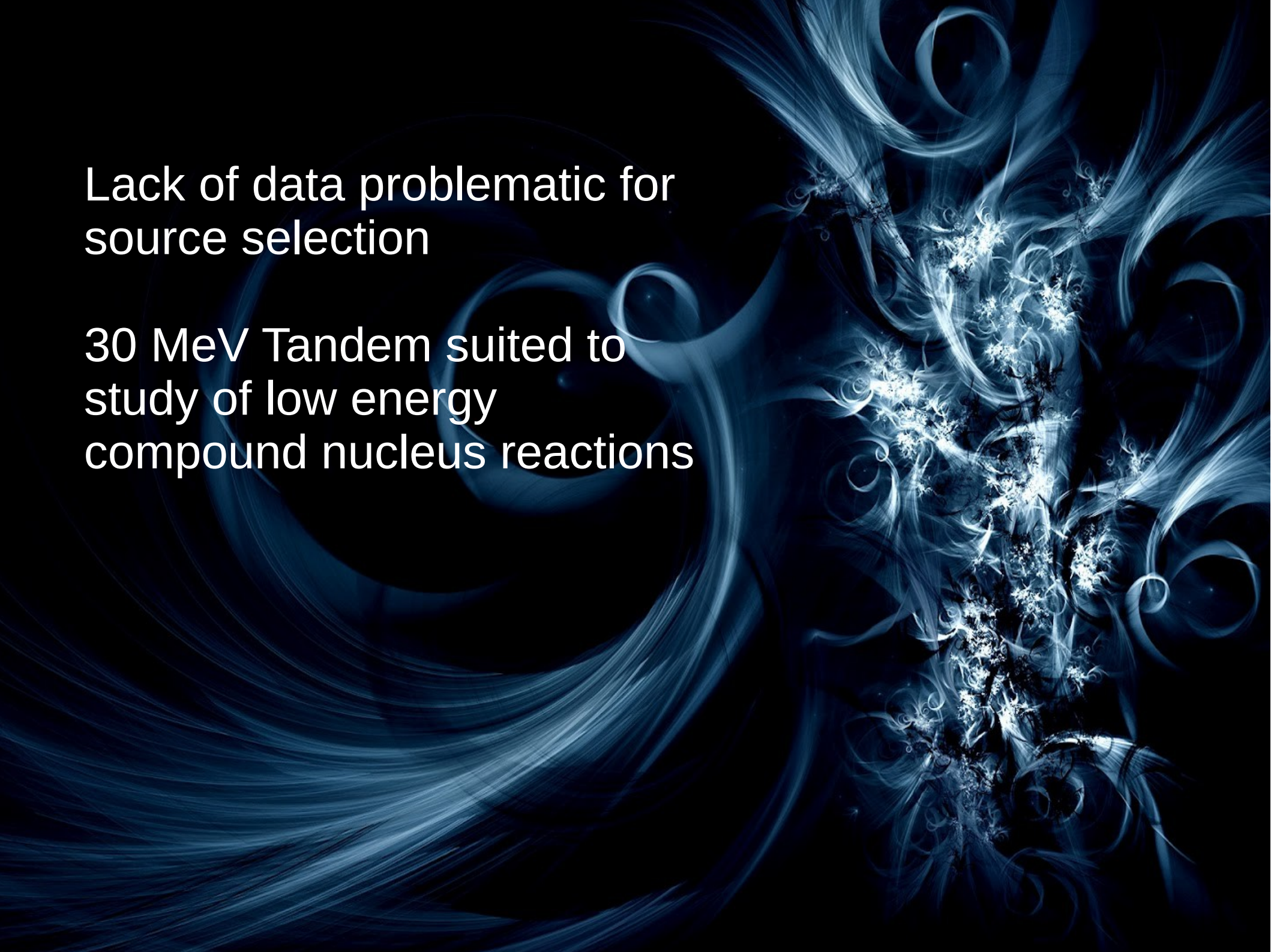
Hadron Therapy
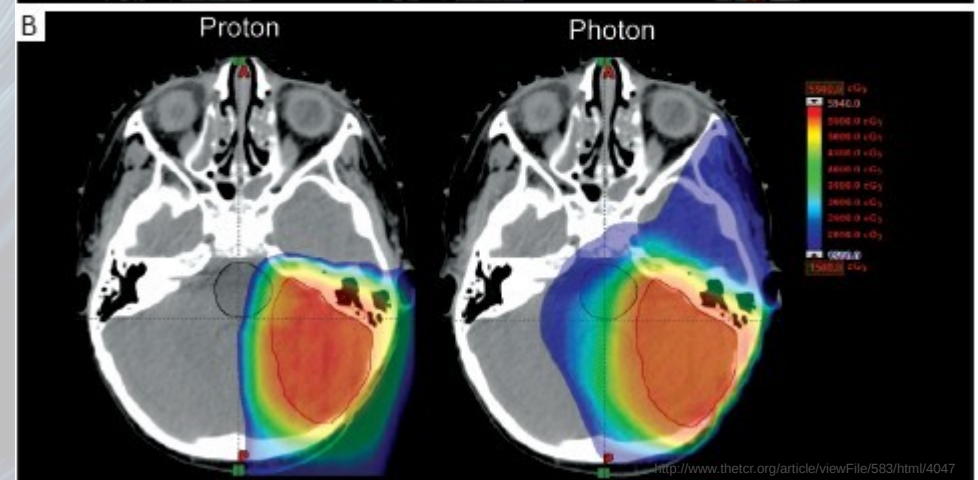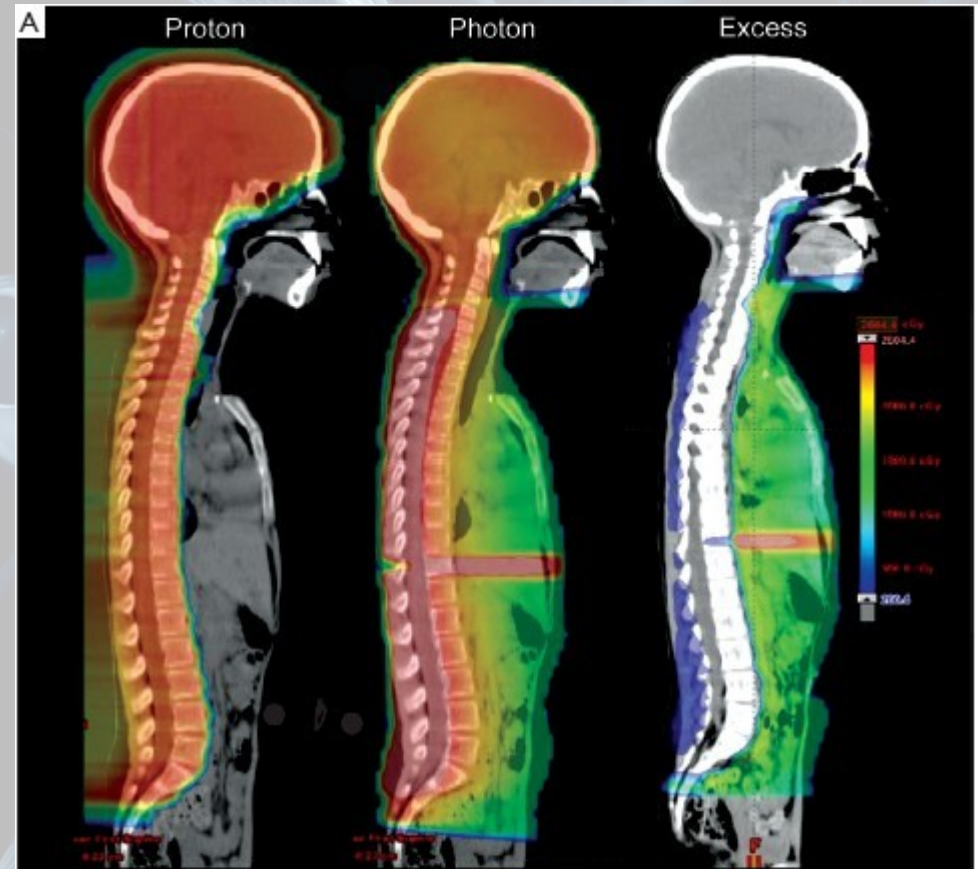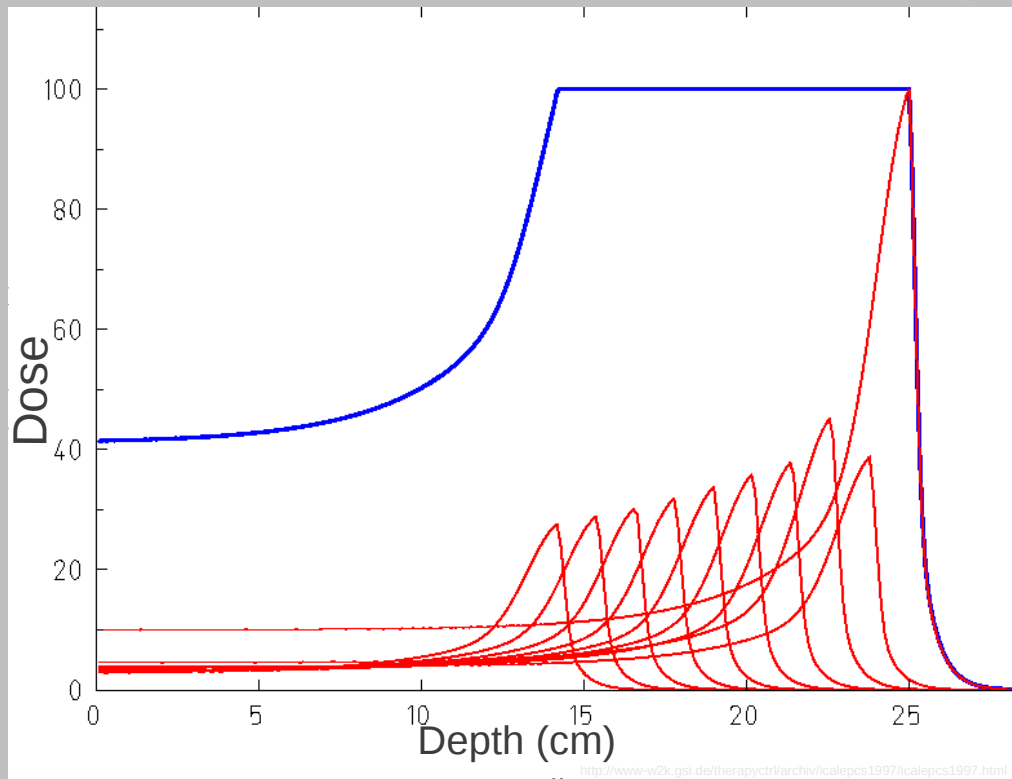
E_p from ~400MeV → 0MeV

Covers all (p,n), (p,2n), (p,n+p), ... resonances

Bone:
Collagen
Calcium(phos/carbon)ate

- C   (99% ^{12}C)

- N   (99% ^{14}N)

- O   (99% ^{16}O)

- P   (100% ^{31}P)

- Ca (97% ^{40}Ca)

https://www.nds.iaea.org/exfor/servlet/X4sSearch5

Plot: ☐ Quick-plot (cross-sections only) ☐ Advanced plot [how-to] using ☐ C5 and ☐ converting ratios to cross sections using [IAEA-standards,2006]
Narrow incident energy (optional), eV: Min: ☐   Max: ☐
☐ Apply ≫ Data re-normalization (for advanced users, results in: C4, TAB and Plots)

| n	Display	Year Author-1	Energy range,eV	Points	Reference	Subentry#P NSR-Key
1)	ⓘ 🔍 6-C-12(P,3N+3P)4-BE-7,,SIG,,,EXP C4: MF=3 MT=?					
2)	ⓘ 🔍 6-C-12(P,N+P)6-C-11,,SIG C4: MF3 MT28					
3)	ⓘ 🔍 6-C-12(P,N+P)6-C-11,IND,SIG C4: MF=3 MT=?					
4)	ⓘ 🔍 6-C-12(P,N+P+A)4-BE-7,,SIG C4: MF3 MT45					
5)	ⓘ 🔍 (6-C-12(P,N+P)6-C-11,,SIG)/(13-AL-27(P,N+3P)11-NA-24,,SIG) C4: MF=3 MT=?					
6)	ⓘ 🔍 (6-C-12(P,N+P)6-C-11,,SIG)/(13-AL-27(P,X)11-NA-24,,SIG) C4: MF=3 MT=?					
7)	ⓘ 🔍 (6-C-12(P,N+P)6-C-11,,SIG)/(6-C-12(P,X)4-BE-7,,SIG) C4: MF=3 MT=?					
8)	ⓘ 🔍 (6-C-12(P,X)4-BE-7,,SIG)/(13-AL-27(P,N+3P)11-NA-24,,SIG) C4: MF=3 MT=?					
9)	ⓘ 🔍 7-N-14(P,2N+2P)6-C-11,,SIG C4: MF3 MT190					
10)	ⓘ 🔍 7-N-14(P,N)8-O-14,,SIG C4: MF3 MT4					
11)	ⓘ 🔍 7-N-14(P,N+P)7-N-13,,SIG C4: MF3 MT28					
12)	ⓘ 🔍 7-N-14(P,X)0-NN-1,,SIG C4: MF3 MT9000					
13)	ⓘ 🔍 (7-N-14(P,N+P)7-N-13,,SIG)+(7-N-14(P,D)7-N-13,,SIG) C4: MF3 MT1003					
14)	ⓘ 🔍 8-O-16(P,2N+2P)7-N-13,,SIG C4: MF3 MT190					
15)	ⓘ 🔍 8-O-16(P,2N+2P)7-N-13,UND,SIG C4: MF=3 MT=?					
16)	ⓘ 🔍 8-O-16(P,2N+4P)5-B-11,CUM/UND,SIG,,,EXP C4: MF=3 MT=?					
17)	ⓘ 🔍 8-O-16(P,2N+5P)4-BE-10,IND/UND,SIG,,,EXP C4: MF=3 MT=?					
18)	ⓘ 🔍 8-O-16(P,2N+P)8-O-14,,SIG C4: MF3 MT41					
19)	ⓘ 🔍 8-O-16(P,3N+3P)6-C-11,,SIG C4: MF=3 MT=?					
20)	ⓘ 🔍 8-O-16(P,3N+3P)6-C-11,UND,SIG,,,EXP C4: MF=3 MT=?					
21)	ⓘ 🔍 8-O-16(P,3N+4P)5-B-10,CUM/UND,SIG,,,EXP C4: MF=3 MT=?					
22)	ⓘ 🔍 8-O-16(P,3N+4P)5-B-10,IND/UND,SIG,,,EXP C4: MF=3 MT=?					
23)	ⓘ 🔍 8-O-16(P,3N+5P)4-BE-9,CUM/UND,SIG,,,EXP C4: MF=3 MT=?					
24)	ⓘ 🔍 8-O-16(P,4N+3P)6-C-10,IND/UND,SIG,,,EXP C4: MF=3 MT=?					
25)	ⓘ 🔍 8-O-16(P,4N+6P)3-LI-7,CUM/UND,SIG,,,EXP C4: MF=3 MT=?					
26)	ⓘ 🔍 8-O-16(P,4N+6P)3-LI-7,IND/UND,SIG,,,EXP C4: MF=3 MT=?					
27)	ⓘ 🔍 8-O-16(P,5N+5P)4-BE-7,,SIG C4: MF=3 MT=?					
28)	ⓘ 🔍 8-O-16(P,5N+5P)4-BE-7,IND/UND,SIG,,,EXP C4: MF=3 MT=?					
29)	ⓘ 🔍 8-O-16(P,5N+6P)3-LI-6,CUM/UND,SIG,,,EXP C4: MF=3 MT=?					
30)	ⓘ 🔍 8-O-16(P,N+P)8-O-15,,SIG C4: MF3 MT28					
31)	ⓘ 🔍 8-O-16(P,N+P)8-O-15,,SIG,,,EXP C4: MF3 MT28					
32)	ⓘ 🔍 8-O-16(P,N+P)8-O-15,IND/UND,SIG,,,EXP C4: MF=3 MT=?					
33)	ⓘ 🔍 8-O-16(P,N+P)8-O-15,UND,SIG C4: MF=3 MT=?					
34)	ⓘ 🔍 8-O-16(P,N+P+A)6-C-11,,SIG C4: MF3 MT45					
35)	ⓘ 🔍 8-O-16(P,X)0-NN-1,,SIG C4: MF3 MT9000					
36)	ⓘ 🔍 (8-O-16(P,2N+2P)7-N-13,UND,SIG)/(8-O-16(P,3N+3P)6-C-11,UND,SIG) C4: MF=3 MT=?					
37)	ⓘ 🔍 (8-O-16(P,N+P)8-O-15,UND,SIG,,,EXP)/(8-O-16(P,3N+3P)6-C-11,,SIG,,,EXP) C4: MF=3 MT=?					
38)	ⓘ 🔍 (13-AL-27(P,N+3P)11-NA-24,,SIG)/(6-C-12(P,N+P)6-C-11,,SIG) C4: MF=3 MT=?					
39)	ⓘ 🔍 15-P-31(P,3N+5P)11-NA-24,,SIG,,,EXP C4: MF=3 MT=?					

1) ⓘ 🔍 6-C-12(P,3N+3P)4-BE-7,,SIG,,,EXP   C4: MF=3   MT=?
2) ⓘ 🔍 6-C-12(P,N+P)6-C-11,,SIG   C4: MF3 MT28
3) ⓘ 🔍 6-C-12(P,N+P)6-C-11,IND,SIG   C4: MF=3   MT=?
4) ⓘ 🔍 6-C-12(P,N+P+A)4-BE-7,,SIG   C4: MF3 MT45
5) ⓘ 🔍 (6-C-12(P,N+P)6-C-11,,SIG)/(13-AL-27(P,N+3P)11-NA-24,,SIG)   C4: MF=3   MT=?
6) ⓘ 🔍 (6-C-12(P,N+P)6-C-11,,SIG)/(13-AL-27(P,X)11-NA-24,,SIG)   C4: MF=3   MT=?
7) ⓘ 🔍 (6-C-12(P,N+P)6-C-11,,SIG)/(6-C-12(P,X)4-BE-7,,SIG)   C4: MF=3   MT=?
8) ⓘ 🔍 (6-C-12(P,X)4-BE-7,,SIG)/(13-AL-27(P,N+3P)11-NA-24,,SIG)   C4: MF=3   MT=?
9) ⓘ 🔍 7-N-14(P,2N+2P)6-C-11,,SIG   C4: MF3 MT190
10) ⓘ 🔍 7-N-14(P,N)8-O-14,,SIG   C4: MF3 MT4
11) ⓘ 🔍 7-N-14(P,N+P)7-N-13,,SIG   C4: MF3 MT28
12) ⓘ 🔍 7-N-14(P,X)0-NN-1,,SIG   C4: MF3 MT9000
13) ⓘ 🔍 (7-N-14(P,N+P)7-N-13,,SIG)+(7-N-14(P,D)7-N-13,,SIG)   C4: MF3 MT1003
14) ⓘ 🔍 8-O-16(P,2N+2P)7-N-13,,SIG   C4: MF3 MT190
15) ⓘ 🔍 8-O-16(P,2N+2P)7-N-13,UND,SIG   C4: MF=3   MT=?
16) ⓘ 🔍 8-O-16(P,2N+4P)5-B-11,CUM/UND,SIG,,,EXP   C4: MF=3   MT=?
17) ⓘ 🔍 8-O-16(P,2N+5P)4-BE-10,IND/UND,SIG,,,EXP   C4: MF=3   MT=?
18) ⓘ 🔍 8-O-16(P,2N+P)8-O-14,,SIG   C4: MF3 MT41
19) ⓘ 🔍 8-O-16(P,3N+3P)6-C-11,,SIG   C4: MF=3   MT=?
20) ⓘ 🔍 8-O-16(P,3N+3P)6-C-11,UND,SIG,,,EXP   C4: MF=3   MT=?
21) ⓘ 🔍 8-O-16(P,3N+4P)5-B-10,CUM/UND,SIG,,,EXP   C4: MF=3   MT=?
22) ⓘ 🔍 8-O-16(P,3N+4P)5-B-10,IND/UND,SIG,,,EXP   C4: MF=3   MT=?
23) ⓘ 🔍 8-O-16(P,3N+5P)4-BE-9,CUM/UND,SIG,,,EXP   C4: MF=3   MT=?
24) ⓘ 🔍 8-O-16(P,4N+3P)6-C-10,IND/UND,SIG,,,EXP   C4: MF=3   MT=?
25) ⓘ 🔍 8-O-16(P,4N+6P)3-LI-7,CUM/UND,SIG,,,EXP   C4: MF=3   MT=?
26) ⓘ 🔍 8-O-16(P,4N+6P)3-LI-7,IND/UND,SIG,,,EXP   C4: MF=3   MT=?
27) ⓘ 🔍 8-O-16(P,5N+5P)4-BE-7,,SIG   C4: MF=3   MT=?
28) ⓘ 🔍 8-O-16(P,5N+5P)4-BE-7,IND/UND,SIG,,,EXP   C4: MF=3   MT=?
29) ⓘ 🔍 8-O-16(P,5N+6P)3-LI-6,CUM/UND,SIG,,,EXP   C4: MF=3   MT=?
30) ⓘ 🔍 8-O-16(P,N+P)8-O-15,,SIG   C4: MF3 MT28
31) ⓘ 🔍 8-O-16(P,N+P)8-O-15,,SIG,,,EXP   C4: MF3 MT28
32) ⓘ 🔍 8-O-16(P,N+P)8-O-15,IND/UND,SIG,,,EXP   C4: MF=3   MT=?
33) ⓘ 🔍 8-O-16(P,N+P)8-O-15,UND,SIG   C4: MF=3   MT=?
34) ⓘ 🔍 8-O-16(P,N+P+A)6-C-11,,SIG   C4: MF3 MT45
35) ⓘ 🔍 8-O-16(P,X)0-NN-1,,SIG   C4: MF3 MT9000
36) ⓘ 🔍 (8-O-16(P,2N+2P)7-N-13,UND,SIG)/(8-O-16(P,3N+3P)6-C-11,UND,SIG)   C4: MF=3   MT=?
37) ⓘ 🔍 (8-O-16(P,N+P)8-O-15,UND,SIG,,,EXP)/(8-O-16(P,3N+3P)6-C-11,,SIG,,,EXP)   C4: MF=3   MT=?
38) ⓘ 🔍 (13-AL-27(P,N+3P)11-NA-24,,SIG)/(6-C-12(P,N+P)6-C-11,,SIG)   C4: MF=3   MT=?
39) ⓘ 🔍 15-P-31(P,3N+5P)11-NA-24,,SIG,,,EXP   C4: MF=3   MT=?

^{12}C: (p,3n+3p)
(p,n+p)

^{14}N: (p,n)
(p,2n+2p)
(p,n+p)

^{16}O: (p,2n+2p)
(p,2n+4p)
(p,2n+5p
(p,2n+p)
...

^{12}C: some data, no (p,n)
^{14}N: includes (p,n)
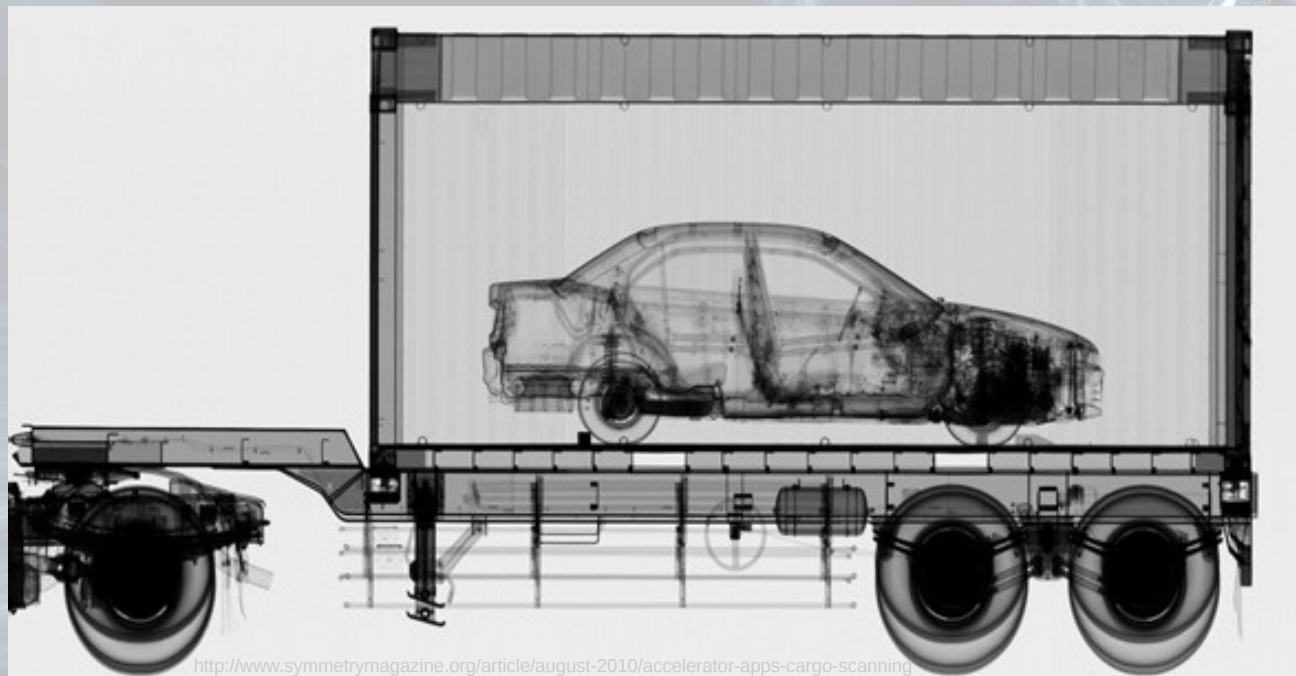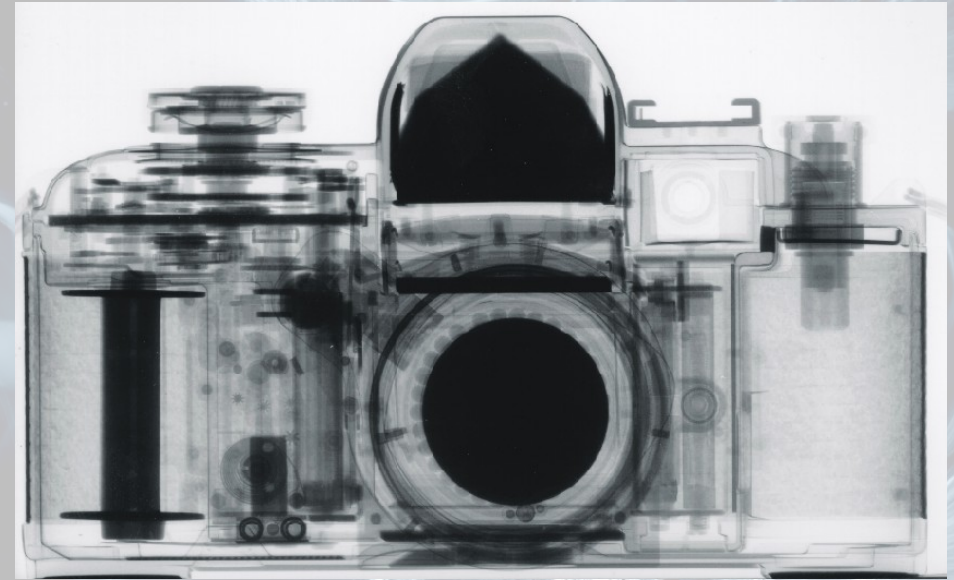^{16}O: lots of data, no (p,n)
^{40}Ca: no data
^{31}P: 4 data points for (p, 3n+5p)

Accurate simulation of neutron production and residual radioisotopes in body impossible

Extracted p, α, ^{12}C (, …?) from Linac and Booster E ~ 400MeV/n study Cross Section etc

Security

http://mnrc.ucdavis.edu/radiography.html

http://www.symmetrymagazine.org/article/august-2010/accelerator-apps-cargo-scanning
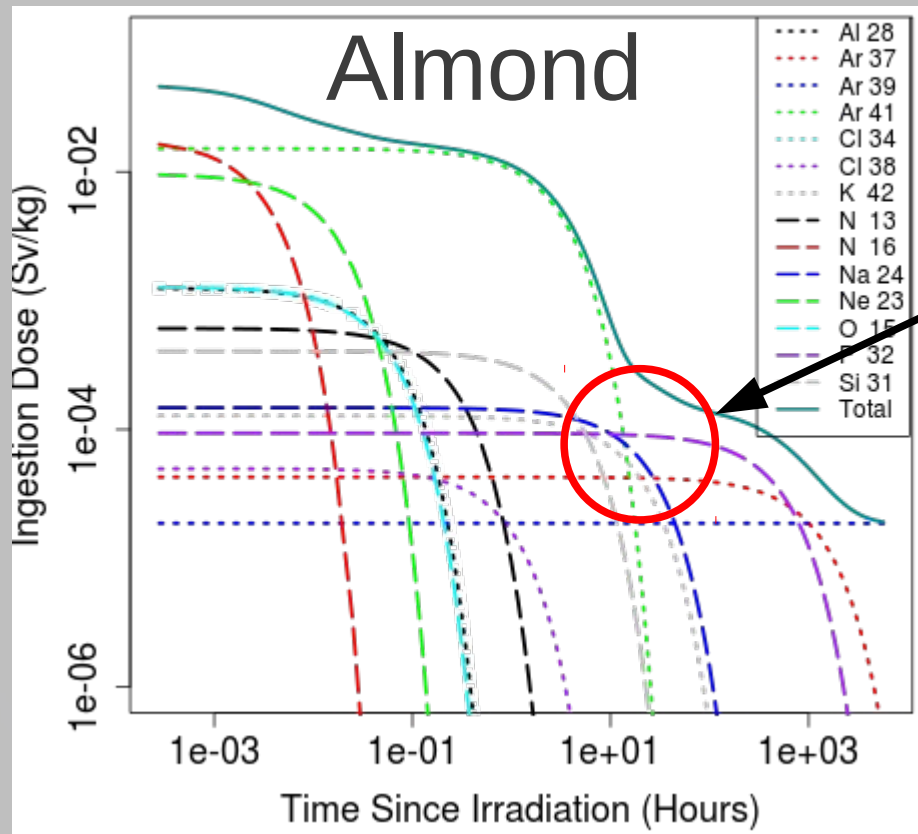
Neutron activation

Consumer goods
  Clothes
  Furniture
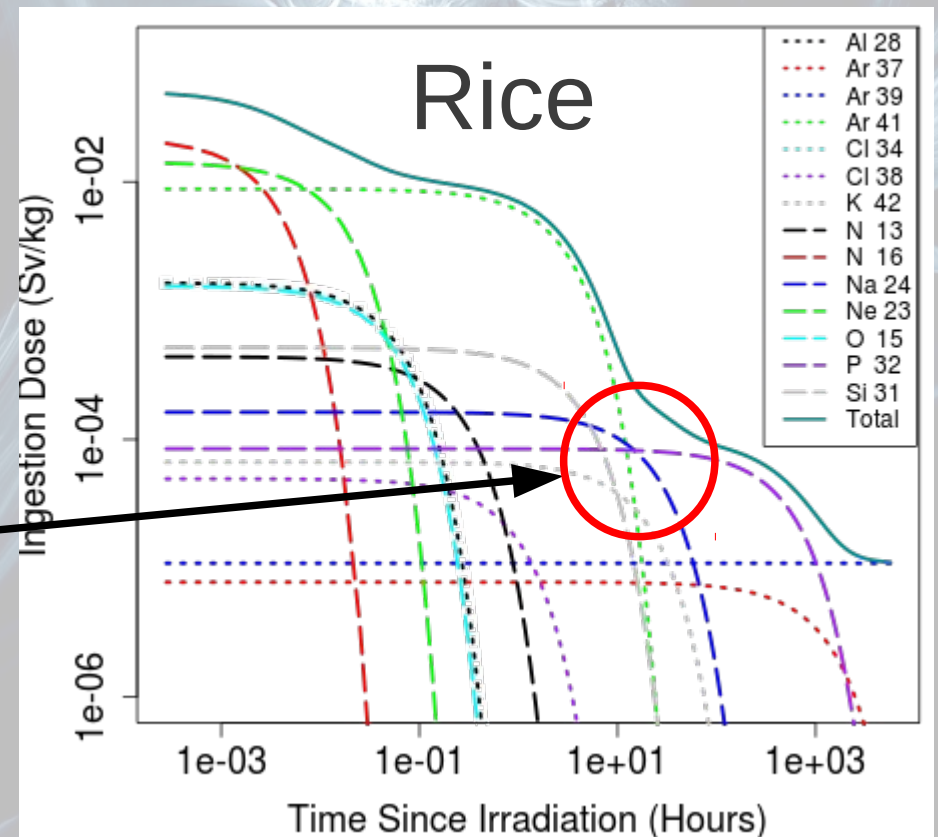 Electricals
  Food

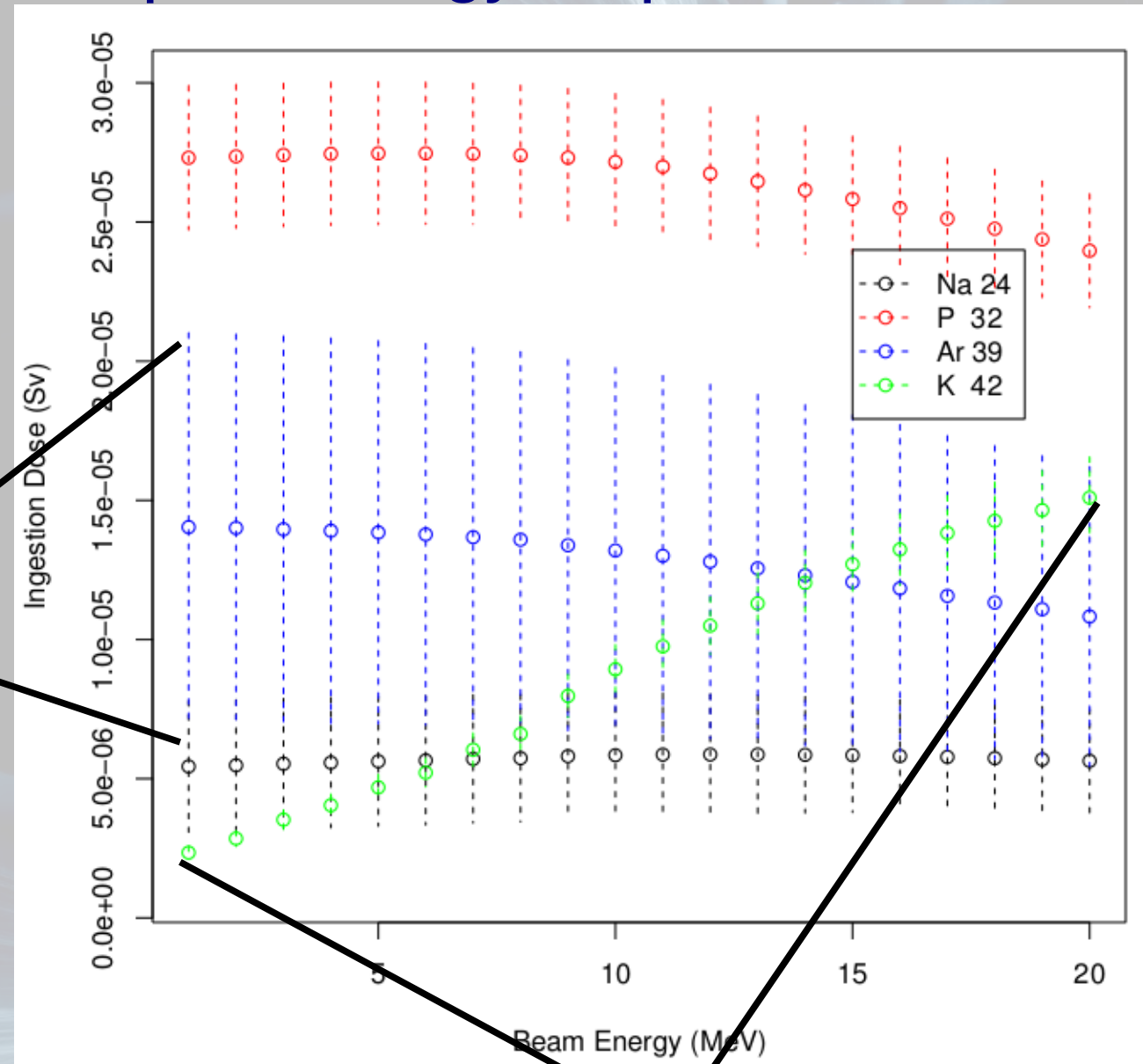^{24}Na identified by EURITRACK collaboration as only serious threat for food

Almond

No ^{24}Na dominance

Brief ^{24}Na dominance

Publication under review

Potato Isotopes Energy Dependance

Large Uncertainties

Strong Energy Dependance

Lack of (n,X) cross-section data prevents accurate understanding of activation

Contact with public requires high level of understanding and safety

nTOF system would enable measurement of neutron induced activation

Conclusion

- Lack of data hampering valuable technology

- Tandem – neutron production

- Linac + Booster – possible radiobiological risks of hadron therapy

- nTOF – Neutron induced activation

Acknowledgements

- Supervisor: Rebecca Seviour

- The University of Huddersfield

- International Institute for Accelerator Applications

- STFC

- Siemens

Thank you for listening